

CESAR: A bottom-up building stock modelling tool for Switzerland to address sustainable energy transformation strategies

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ARTICLE INFO

Article history:

Received 17 November 2017

Revised 17 January 2018

Accepted 6 March 2018

Available online 10 March 2018

Keywords:

Building stock model

Dynamic building simulation

Neighbourhood

Retrofitting

Climate change

ABSTRACT

This paper presents the building stock model CESAR (Combined Energy Simulation And Retrofitting), which is based on bottom-up modelling methodology for the development of sustainable energy transformation strategies for the buildings in Swiss districts. CESAR is composed of two sub-models: a Demand Model (DM) and a Retrofitting Model (RM). The DM is tasked with identifying the current energy demand of buildings in districts. It builds on geo-referenced information and available census data, and its flexibility allows it to be applicable to any kind of residential neighbourhood within Switzerland. The DM is based on an automated bottom-up modelling technique, which employs the dynamic building energy simulation software tool EnergyPlus as its simulation core to generate hourly energy demand profiles of individual buildings taking the interactions with neighbouring buildings (e.g. shading and solar inter-reflections) into account. Once current energy demands are calculated by the DM, the RM further offers the possibility to apply a set of energy transformation scenarios, based on the Swiss Energy Strategy 2050, to generate future demand and emission projections of districts including key economic indicators. Besides that, the building energy performance under climate change projections can be evaluated.

In this paper, the tool is applied on three case study districts, an urban, suburban and rural area, within Switzerland and different transformation scenarios according to the Energy Strategy are investigated. Results revealed significant differences between the two implemented transformation scenarios, the Business as Usual (WWB) and the New Energy Policy (NEP). While in the WWB scenario, only a small number of buildings reaches the intended targets for primary energy and GHG emissions until 2050, the NEP scenario induces a much higher transformation of the districts. Besides that, the significance of the impact of global warming on future cooling demand is shown.

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1. Introduction

1.1. Background

To meet greenhouse gas (GHG) emission reduction targets a considerable change in the current structure of countries' energy systems is required. This includes next to the decarbonisation of the energy supply, also a significant reduction of the current energy consumption. The building stock plays thereby an important role by contributing with about one third to the total GHG emissions in Switzerland [1] and similar numbers in many other coun-

tries. Different energy politic models have been developed to identify the overall GHG emission targets for the future and the respective measures required to achieve them. One of these concepts is the 2000-Watt Society [2], which propagates the reduction of the overall average primary energy usage to 2000 W per person by the year 2150. To reach this goal, the Swiss standard SIA 2040 [2] provides in-between targets in terms of yearly primary energy consumption and GHG emissions for the Swiss building stock to be met by 2050, shown in Table 1. Primary Energy and GHG emissions targets are specified according to the state of building (newly built or during retrofitting of the building envelop and system replacement) and phases of buildings life-cycle, whereby the building construction phase refers to embodied carbon and primary energy of materials during retrofitting.

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<https://doi.org/10.1016/j.enbuild.2018.03.020>

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Nomenclature

ACH	Air Changes per Hour
CESAR	Combined Energy Simulation And Retrofitting
CHF	Schweizer Franken (Swiss Francs)
DHW	Domestic Hot Water
DM	Demand Model
ERA	Energy Reference Area
GHG	Greenhouse Gas
GIS	Geographical Information System
GWR	Gebäude- und Wohnungsregister (Buildings and Apartments Registry)
IDF	intermediate data format
MFB	Multifamily Building
NEP	Neue Energiepolitik (New Energy Policy)
PEN	Primary Energy (non-renewable)
RCP	Representative Concentration Pathways
RM	Retrofit Model
Rp.	Rappen (Swiss Cents)
SES 2050	Swiss Energy Strategy 2050
SFB	Single Family Building
SIA	Schweizerischer Ingenieur- und Architektenverein (Swiss Engineers and Architects Association)
TMY	Typical Meteorological Year
WWB	Weiter Wie Bisher (Business as Usual)

After the nuclear accident in Fukushima, Switzerland has decided to phase out nuclear energy, and developed the Swiss Energy Strategy (SES) 2050 [3], which defines goals to reduce current energy consumption, including retrofitting rates that should be achieved by the housing stock of Switzerland. To address the goals different measures are targeted, which include updating the building envelope, changing to more environmental friendly heating systems and more energy efficient home appliances and lighting technologies. In order to devise effective strategies that will allow Switzerland to reach these targets, first, sufficient knowledge of the current energy consumption of buildings is essential.

Currently, detailed energy demand information at the individual building and the city quarter level is still lacking. Available information (if any) is usually limited to energy bills at a yearly resolution. Only a few smart-metering campaigns are trying to investigate what is happening at the low-distribution grid on a more resolved temporal scale. With the integration of intermittent renewable and other decentralized energy systems, time-resolved energy demand information is required in order to detect high or low demand and supply periods within a quarter, and subsequently to decide how available energy can be effectively generated, distributed or stored.

Housing stock modelling approaches include both bottom-up and top-down approaches [4,5]. Many countries have developed top-down modelling approaches to identify the energy consumption of their building stock and potential changes of its consumption in the future. These modelling approaches are typically based on econometric and technological models [4], which calculate the demand based on aggregated economic variables and other available data. Since these models are mainly based on historical data,

predictions into the future are less appropriate and are not suitable for identifying the energy performance of specific buildings and neighbourhoods.

More recent developments include bottom-up models, which typically rely on physically-based modelling techniques. These models are building up on already well-established methods in the building energy simulation domain, but in a more simplified manner to account for physical processes not only within a single building, but also within whole neighbourhoods or cities. Available modelling techniques differ substantially, and include next to steady-state [6–10] also dynamic heat-balance models [11–16], while differences in building modelling resolution are observed ranging from single zone [6–8,11] to multi-zone models [13–16].

The drawback of modelling multiple buildings is that various types of input information is required. Since such information is typically not easily available, archetypical modelling approaches have been developed, which cluster buildings based on typical characteristics such as building type, floor area, climate or construction type and use this information as input information for buildings in the respective cluster. The considered number of archetypes varies substantially ranging from less than 15 archetypes [8,10] up to 100 s [11,12,17] and even 1000 s [18]. A recent review paper gives a detailed summary on the different methodologies, the required input information and validation studies [19].

For Switzerland different approaches have been considered [9,12,20–23] whereby the studies have different focuses. For example, Aksoezen et al. [21] developed a methodology to study differences in building energy consumption depending on their age for the city of Basel. Perez et al. [23] used the tool City-Sim to investigate retrofitting potentials for a specific district in Zurich. Orehounig et al. [22] and Froemelt and Hellweg [24] focus in their studies on validating different modelling approaches by comparing simulation results with measured energy demand data. The latter of the two approaches was also used in an earlier study, to perform a life-cycle assessment of housing and land-based mobility for the municipality of Wattwil [9]. Fonseca and Schlueter developed a modelling framework to evaluate retrofitting options for a Swiss district [12] and then combined the tool with an optimization framework to identify optimal system configurations [25]. Future scenarios, which have been put in the context of future emission goals have been investigated in [10], where a bottom-up housing stock model is combined with technology diffusion and retrofitting rates to investigate the potential of the housing stock to contribute to the 2000-Watt Society goals.

Until now, many of the available modelling methodologies focus on yearly or monthly values for the building energy demands, an approach which can be considered valid for assessing the current energy demand of a neighbourhood or to identify future retrofitting options. However, to evaluate possibilities for demand response, to address capacities of storing heat in building mass, but also to sufficiently integrate renewable energy and short and long-term storage technologies more time-resolved data are needed. Thereby a crucial point is to account for the variability within people's behaviour during the course of a day, to avoid unrealistic peaks in energy consumption at a specific point in time but also to take the variability of building characteristics between different buildings into account.

Table 1

Primary energy consumption and Greenhouse Gas (GHG) emission targets for the Swiss building stock in the year 2050 towards a 2000-Watt Society.

	Primary energy [MJ-eq/m ²]		GHG emissions [kg CO ₂ -eq/m ²]	
	New	Retrofit	New	Retrofit
Building construction phase	110	60	8.5	5
Building operation phase	200	250	2.5	5

Moreover, most of building retrofitting within a neighbourhood does not occur within a specific time-period e.g. a year, but is performed over a time-span of many years. For Switzerland, specific goals for reducing the primary energy consumption and CO₂ emissions until the year 2050 are formulated in the SES 2050 [3] which target, depending on the scenario, different retrofitting rates per year. By combining building stock models with technology diffusion and future retrofitting rates, a detailed assessment of possible transformation paths of a neighbourhood can be achieved. With this, future energy consumption and emissions of the neighbourhood under different scenarios can be compared and it can be evaluated if they are in line with the overall goals in emission reduction of the municipality or country.

1.2. This paper

Based on this background, this paper presents a building simulation tool based on a bottom-up modelling method for the development of sustainable energy transformation strategies of buildings in Swiss districts. The tool is composed of two individual models: a Demand Model and a Retrofit Model. With this tool the current energy demand and future retrofitting potentials for Swiss districts can be assessed. The tool allows to compute hourly resolved demand profiles at individual building level and thereby takes shading and reflections of neighbouring buildings into account. The model further accounts for the variability of building characteristics and occupant behaviours among different buildings to ensure a realistic representation of energy demand data aggregated at the urban level. The automated approach is built on geo-referenced information and available census data, which allows to be applied to any kind of residential neighbourhood within Switzerland. Once the energy performance of the current building stock is identified, the retrofitting model allows to study different retrofitting scenarios of the SES 2050. Future scenarios include various envelope retrofit scenarios, building system updates, changes in electricity supply mixes and additionally accounts for changing building energy performance due to climate change. Results can be computed in terms of energy demand, GHG emissions but also resulting costs for the building retrofits.

2. Modelling approach

A simulation tool named “Combined Energy Simulation And Retrofitting [CESAR]”-tool is developed which is based on a bottom up modelling approach. The tool is composed of two models, the Demand Model (DM) which is the simulation engine to compute hourly energy demand profiles for buildings, and the Retrofit Model (RM) to assess different transformation studies of the district based on the SES 2050. Fig. 1 shows the workflow of the tool. The energy performance of all buildings in a neighbourhood are assessed with the DM. Input information, which is required for modelling the buildings, is provided by different databases. This information includes assumptions to model the current situations of a district or for future years under different retrofitting scenarios. Input information to represent the current situation of the building stock of Switzerland includes building statistical data [26] to represent *today's building characteristics* such as materials, construction types, infiltration rates and glazing ratios. Additionally assumptions for *internal conditions* pertaining to user behaviour, thermal settings (heating and cooling set point temperatures), lighting and appliances and ventilation rates are based on [27]. 2.5D building information [28] is used to represent *buildings geometry* including orientation and shading by neighbouring buildings. Typical meteorological years (TMY) weather files [29] for different locations in Switzerland are included in the database to represent *local weather conditions*.

Once the current situation of the building is simulated with the DM, the RM provides input information on different transformation strategies for buildings. Transformation strategies are based on targets and assumptions in accordance to the SES 2050. Input information includes *retrofit of building envelope* with relevant parameters such as retrofitting rates for different building ages and building element combinations (e.g. walls, windows etc.) and *update of building systems* taking into account projected shares and changing efficiencies of the systems given in the SES 2050 into account. Projections on *internal conditions* with information on changes in lighting and appliances efficiencies are also considered. Additionally information on future weather conditions under climate change are included in the model. Based on these assumptions changes in energy demand of these buildings for future years (2020, 2035, 2040 and 2050) are simulated with the DM and information is again passed on to the RM for a performance evaluation. To calculate current and future GHG emissions for the scenarios *PEN emissions and primary energy* factors and projected trends of the Swiss electricity mix based on the SES 2050 are considered. For calculating resulting *operating and investment costs* for both retrofitting of the building envelope and system changes information from Gebäudeenergieausweis der Kantone (GEAK) [30] is implemented in the RM. GEAK is a cantonal building energy performance certificate, which uses a classification to show the energy quality of a building. It is comparable to the energy label for household appliances. Finally the CESAR tool outputs results for individual buildings, which include current and future energy demands for heating, domestic hot water, cooling and electricity at an hourly resolution, as well as annual totals of primary energy consumption and GHG emissions due to the operation of the building and the embodied energy in the building retrofit measures. Besides operational and embodied energy, economical aspects of the different retrofit measures are computed. The core of the CESAR tool is implemented in Matlab with a graphical user interface to both the DM and RM. The tool calls the building simulation software EnergyPlus to simulate the buildings, and post-processes and analyzes the results. Other tools which are incorporated in the methodology include ArcGIS [31] and Meteonorm [32], which are used to create detailed input files such as building footprint vertices and local weather files, respectively. The information chain and workflow with corresponding tools are described in detail in the following section.

2.1. Demand Model (DM)

In order to calculate the building level energy demands, collected information on building geometry, characteristics, internal conditions and geographical location (which is further described below) is processed to define input information for the simulation tool EnergyPlus [33] for each individual building. The simulation engine EnergyPlus is a detailed dynamic energy analysis and thermal load simulation tool, which is capable of simulating loads and systems in the same time step. The advantage of applying an already well-established building simulation tool at the urban scale lies in the possibility to model a building in a simplified way in cases of limited available information, but also to have the option to model the building more in detail if needed. An automated workflow generates an EnergyPlus input file (IDF-file) for each building including also the 3D information of neighboring buildings and thus allowing the consideration of building interactions. By calling the operating system to run the EnergyPlus files, dynamic load profiles are generated automatically for each building. The process is repeated until loads for all buildings in a district are simulated. More information on defining the geometry and additionally relevant input information is provided in the next sections.

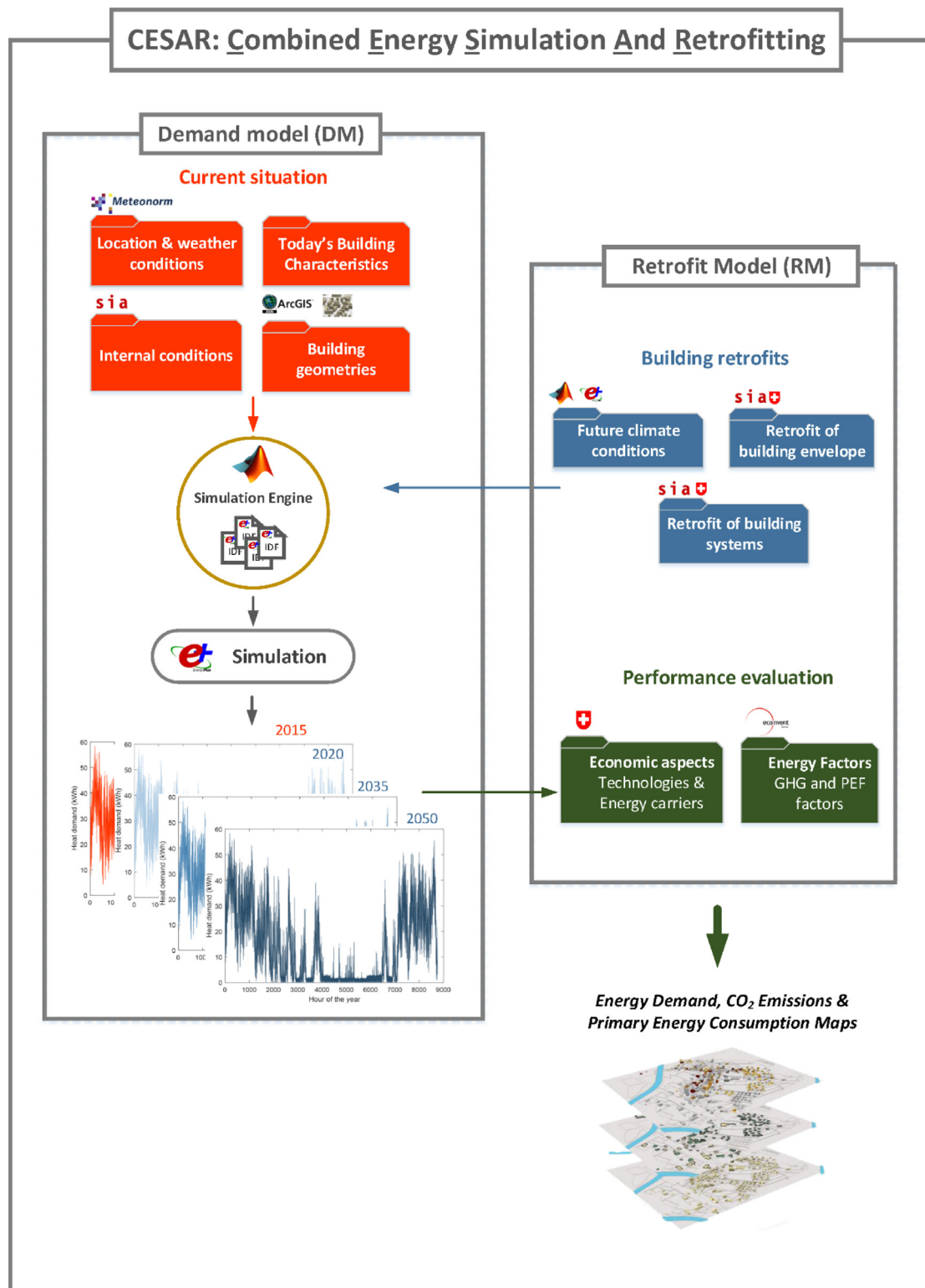


Fig. 1. CESAR tool workflow and modelling concept.

2.1.1. Building geometry

Accessible geographical information for Swiss buildings in the form of 2.5D GeoData [28] is pre-processed through a Geographical Information System, such as ArcGIS [31] in order to define the geographical coordinates of the floorplan vertices. Based on the building floorplan and the building height, a single 3D thermal zone for each floor of the buildings is created taking floors,

walls, roofs and window constructions into account. 2.5D GeoData of Swiss buildings define not only building size and shape itself, but also the absolute geographical location and orientation of each building. This provides abundant geometrical information for any specific building in a neighbourhood. Moreover, it allows to incorporate interactions among the buildings in a certain distance with regards to external shading and solar inter-reflections. According

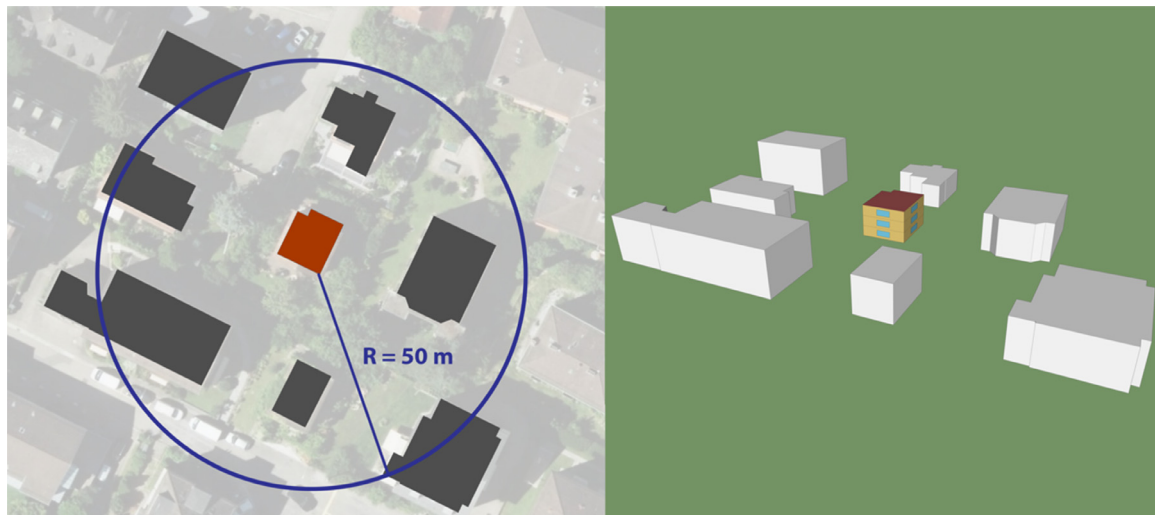


Fig. 2. Example model input (2D footprint) and visualization of the generated corresponding EnergyPlus model of a building and its neighbourhood represented as shading objects.

to global geographical coordinates, buildings in a neighbourhood are clustered within a circular area for each building as the origin (see Fig. 2). The size of the circular area is case dependent and can be set by the user. Within each simulation run, the central building is modelled in detail assuming typically one zone per floor, thereby accounting for multiple thermal zones within a building. The neighbouring buildings are modelled as shading objects in order to account for local shading through the buildings but also for beam and sky solar radiation that is reflected from exterior surfaces which then strikes the central building. The radius of the area can be modified within the model to fit the building density of the district. Fig. 2 shows the 2D footprint of an example building and its neighbouring buildings (left), and resulting IDF file generated by the DM (right, visualized in SketchUp)

2.1.2. Building characteristics

Other, non-geometry related, building characteristics are additionally required. Relevant input information pertains to building construction, type and usage, as well as building systems, glazing ratios and infiltration rates. The suggested modelling approach builds on census data and Swiss building statistics [26] where for each building in Switzerland information on the building construction year, current heating and domestic hot water systems and building type is available. In order to use this information for building simulation, it has to be further processed. However, input information for most of the required building characteristics that is reliable and consistently available throughout Switzerland is difficult to retrieve at individual building level without a detailed analysis. Therefore, an archetypical approach, which clusters buildings according to building location, type of building, and year of construction is considered. This archetypical approach defines material properties, construction settings, glazing ratios and infiltration rates for groups of buildings of a similar building type (e.g. residential, office,...) and of a certain construction year period. As a starting point, only residential buildings are taken into account.

2.1.2.1. Constructions. Construction methods and thus the resulting heat transfer coefficients (U -values) of building elements have changed considerably over time. A categorization, which clusters construction types depending on the year of construction is adopted in the model. Construction information from literature is integrated in the model, which represent typical construction types depending on the year and location. Further information on the approach and literature sources can be found in Appendix A.

Table 2

Average efficiencies of heating and DHW systems in status quo (2015).

System	Efficiency heating	Efficiency DHW
Oil boiler	0.86	0.66
Gas boiler	0.93	0.73
Coal boiler	0.74	0.74
Wood boiler	0.72	0.48
Electric heating	0.91	0.79
Heat pump	3.00	2.73
Solar thermal	0.86	0.73
District heating	0.92	0.77

2.1.2.2. Building systems. Building systems, such as heating and domestic hot water systems, and their efficiencies are crucial for the calculation of the final and primary energy consumption as well as the GHG emissions of buildings. The different available technologies for heating and DHW exhibit highly diverse efficiencies and emission factors. Census data in Switzerland include information about energy carriers for heating and DHW systems on building level. Based on this information, a set of heating systems and their typical efficiencies are defined and provided to the DM. Table 2 shows the different available systems and their average efficiencies in 2015, based on data from the SES 2050 [3].

2.1.2.3. Glazing ratio. In case detailed information on the Window to Wall Ratio (WWR) is available at the individual building level, a building-specific ratio is considered in the DM. However, since there is a common lack of WWR data at individual building level, an archetypical approach based on the year of construction is adopted. Resulting WWR ranges are shown in Appendix B, whereby each building gets a random WWR value within the uncertainty range assigned based on its year of construction.

2.1.2.4. Infiltration rate. Infiltration rates are, likewise WWR and constructions, adopted according to an archetypical approach. Information on literature sources can be found in Appendix B.

2.1.3. Internal conditions

Building energy simulation tools require additional input data to represent the building's internal conditions regarding the occupants' presence, activities and their indoor environment preferences. These inputs are a combination of scalar values (e.g. the

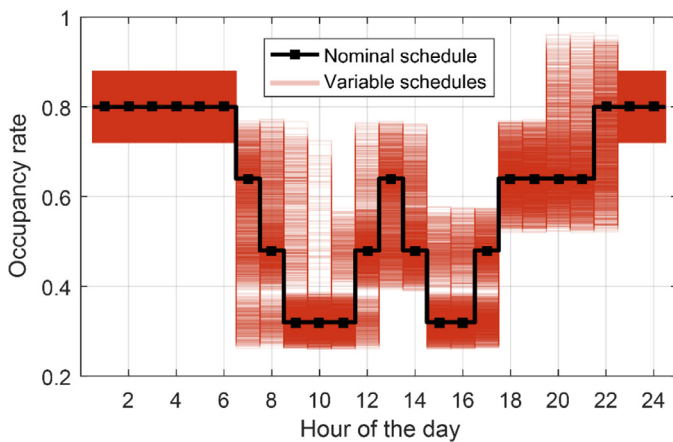


Fig. 3. Exemplary nominal and stochastic occupancy profiles for a residential building in a day.

nominal floor area per person (m^2/P), the installed lighting capacity (W/m^2), thermostat settings ($^{\circ}\text{C}$) etc.), and of information about the temporal variation of the occupants' presence, activities and indoor settings, usually referred to as schedules. A complete overview of these parameters is given in [Appendix C](#). Such information is standardized for Swiss buildings in the norm SIA 2024, which contains different values and schedules according to building usage.

Assigning the same input data to each individual building in a neighbourhood, though, neglects building diversity in terms of occupant densities, appliance ownerships etc., but also in terms of the stochastic occupant presence and activity patterns. Such a practice would result in unnaturally similar energy demand patterns of the buildings, which when aggregated for the whole neighbourhood would lead to peak energy demands that are higher than the ones that would occur in reality due to occupant behaviour diversity.

In order to account for building diversity in the DM, first, a probability distribution is assigned to each of the scalar values required for the internal conditions of each building. These are given in more detail in [Appendix C](#). Additionally, variability is also introduced to the occupant presence and activity schedules of each building by generating a large number of stochastic schedules with a two-step approach described in [Appendix C](#). An example for a day's nominal and stochastic occupancy profiles for a residential building is given in [Fig. 3](#). Then, in order to reproduce building diversity in the DM, each individual building in the neighbourhood is assigned different values for the scalar parameters sampled from their respective probability distributions and different stochastic schedules.

2.1.4. Location and weather conditions

For the representation of the outdoor conditions, local weather data at hourly resolution are required. Switzerland disposes of a number of weather stations, which monitor information on temperatures, relative humidity, solar radiation, wind direction and wind speed. This information is available through Meteoswiss [\[34\]](#) and already processed by the weather file software Meteotnorm [\[32\]](#). Based on these data a database of EnergyPlus weather files (epw) is generated and connected to the DM in order to represent external weather conditions of relevant locations.

2.2. Retrofit Model (RM)

Once the current situation of buildings is analyzed with the DM, the Retrofit Model (RM) allows for an assessment of differ-

ent future building stock transformation scenarios and an analysis of the reduction in energy demand and emissions to address targets of Switzerland [\[3\]](#). In addition, embodied energy and emissions due to retrofit measures as well as an estimation of costs for the building stock transformation are computed. The model offers predefined transformation scenarios based on the SES 2050 [\[3\]](#), namely the Business as usual (WWB) and the New Energy Policy (NEP) scenario, but also allows to implement other user-defined scenarios. The *WWB scenario* is based on actual trends in transformations and efficiencies of buildings, energy consumption and production. The *NEP scenario* is based on the intended reduction in primary energy consumption and GHG emissions by 2050 on the way to the 2000-Watt Society.

Beside retrofit measures at the building envelope, future system transformations and efficiency improvements are taken into account. The assignment of retrofit measures, such as a retrofit of the building envelope or a replacement of the heating or DHW system to a building is based on a random selection, following the rates and shares of the transformation scenarios. This approach is implemented due to the absence of regulations which would prescribe a retrofit of the worst buildings first.

The RM provides information and results for the following 5 retrofit periods, 2015–2020, 2020–2030, 2030–2035, 2035–2040 and 2040–2050, while the year 2015 serves as the reference for the retrofit analysis.

2.2.1. Retrofit of the building envelope

To estimate the reduction in space heating demand due to retrofit of the building envelope, different retrofit rates are considered by the RM depending on the year of retrofitting and the year of building construction. Assumed retrofit rates (in terms of percentage of buildings retrofitted) for different construction years are taken from the SES 2050 [\[3\]](#). [Fig. 4](#) shows an example of average annual overall retrofit rates of single-family buildings (SFB) for each retrofit period in the WWB and the NEP scenario. Additionally more detailed assumptions going down to various building parts are taken from a study about the Swiss building stock [\[35\]](#). Further details on the approach are given in [Appendix D](#).

2.2.2. Retrofit of building systems

Building systems and their transformation have a significant impact on the primary energy consumption and GHG emissions of a district. The RM considers various system developments, including update of heating and DHW systems and changing efficiencies of future technologies such as lighting and other electrical appliances.

The transformation of the systems are applied to each building independent from system replacements or building envelope retrofit. This assures that the average Swiss electricity consumption (due to lighting and appliances) and the average system efficiency (DHW and space heating) are aligned with the SES 2050.

2.2.2.1. Lighting equipment and electrical appliances. The scenarios of the SES 2050 predict a reduction in the electricity consumption for lighting due to a replacement of old light bulbs with highly efficient LEDs. For electrical appliances (e.g. computers, kitchen equipment, mobile phones) it is assumed that efficiencies will improve. However, the average number of installed appliances in a typical household is predicted to increase. Overall, a minor reduction of the nominal power density from appliances is expected for future scenarios which has not only an impact on the total electricity consumption, but also on internal heat gains and subsequently on the cooling and heating demand of buildings. Respective assumptions both for lighting and electrical appliances are implemented in the RM.

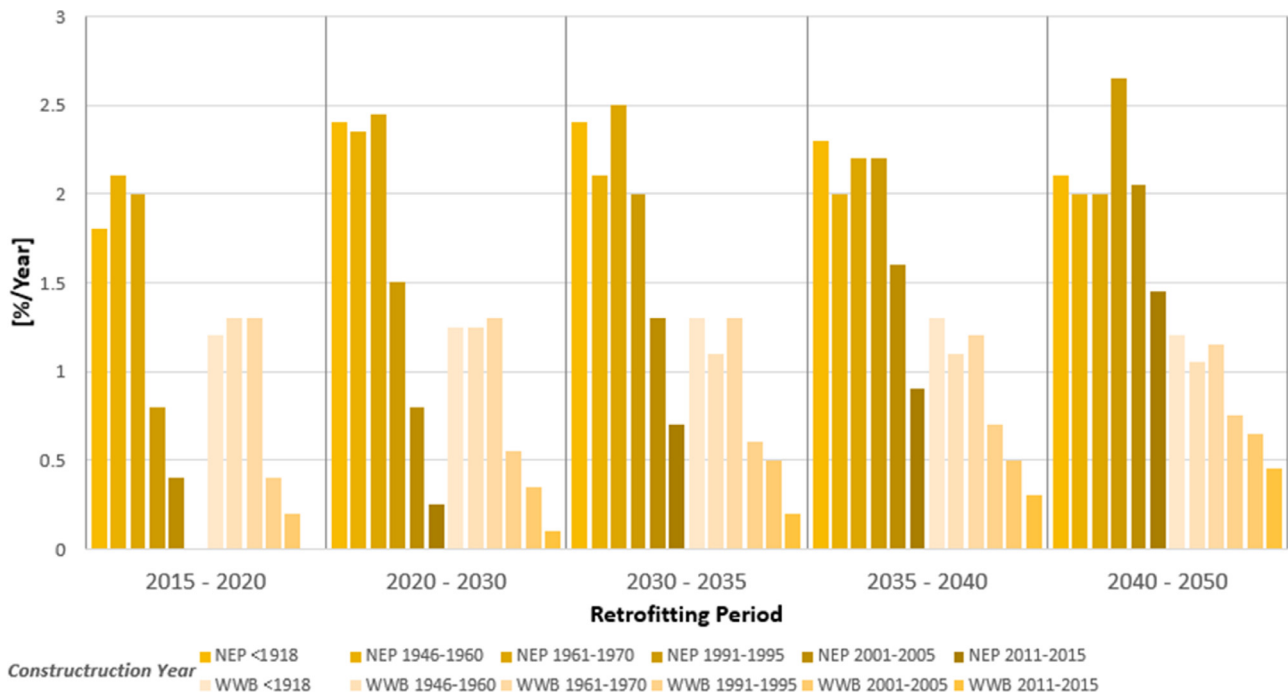


Fig. 4. Annual envelope retrofit rates for SFB of different construction years for the five implemented retrofit periods.

2.2.2.2. Heating and DHW system shares and efficiencies. In each scenario of the SES 2050, a transformation of the heating and DHW system shares for future time periods are considered. During each retrofit period, some of the existing building systems are randomly selected and replaced by new systems in accordance to annual system shares given in the SES 2050. In the transformation scenarios, it is further assumed that system efficiencies will improve and therefore the total fuel and electricity consumption will be reduced.

2.2.3. Future climate conditions

Climate change is an additional challenge for modelling the energy demand of existing and new buildings, which has to be taken into account. Buildings need to perform efficiently and ensure a comfort indoor environment under current and future climate conditions. Therefore, an additional use of the developed tool is the assessment of climate change impacts on buildings at urban scales. Using high-resolution regional climate change projections from the CORDEX project [36], any weather file for any location in Switzerland (e.g. from Meteonorm) can be transformed into a series of climate change weather files for every single year until 2100 with the morphing algorithm [37]. Thereby, climate change weather files are created for a subset of six models¹ from the CORDEX project and two Representative Concentration Pathways (RCP), namely rcp45 and rcp85, representing an intermediate and high GHG concentration scenario [38]. These weather files can be utilized to calculate future energy demand patterns for buildings, investigate the short and long-term impacts of climate change on the building stock, and develop retrofit strategies that ensure optimal building performance for all possible future climatic conditions. Respective future weather files are collected in a database, which serves as an input for the RM.

2.2.4. Performance analysis

Energy demands for space heating, DHW, electricity and cooling are simulated at hourly resolution for an entire year with the DM

for the current situation and future retrofitting strategies. Output information is collected in a database at building level in hourly resolution for a whole year and is further processed to account also for GHG emissions, primary energy consumptions and emissions for operation and construction as well as economic aspects such as investment costs and payback times.

2.2.4.1. GHG emission and primary energy factors. Primary energy consumption from non-renewable sources and GHG emissions are calculated based on the installed systems. In addition, embodied non-renewable primary energy consumptions and GHG emissions due to retrofit measures including building envelop retrofit and systems replacement of systems are calculated from a life cycle assessment viewpoint. Furthermore, primary energy consumption and emission data for operation and construction is compared to the targets of the 2000-Watt Society which are shown in Table 1.

Due to a continuously increasing electrification of the building heating sector in Switzerland via the adoption of heat pump systems [39], the electricity mix and its environmental impact plays a significant role in calculating the total primary energy consumption and GHG emissions of a district. The Swiss government decided in 2011 to shut down the nuclear power plants gradually by 2034 [40]. Therefore, other technologies, in the WWB most likely gas combined cycle power plants and in the NEP a high share of renewables, will be implemented to cover the electricity supply gap.

This change in electricity production and the effects on the primary energy consumption and emissions was assessed by Stadt Zürich [41] for the different scenarios presented in [3], whereby a differentiation is made between electricity consumption with the supply mix (with trade) or the production mix (without trade). In the SES 2050 the factors of the supply mix are considered accordingly.

Table 3 shows the predicted trend of the primary energy factors (PEF) non renewable [MJ-oil-eq/MJ] and the GHG emission coefficients [kg CO₂-eq/MJ] for the Swiss electricity mix as it is implemented in the model for the transformation scenarios WWB and

¹ CNRM-CM5-CCLM4-8-17, EC-EARTH-CCLM4-8-17, EC-EARTH-HIRHAM5, EC-EARTH-RACMO22E, IPSL-CM5A-MR-WRF331F, MPI-ESM-LR-CCLM4-8-17.

Table 3

Primary energy factors and GHG emission coefficients for the Swiss electricity mix based on the transformation scenarios NEP and WWB.

	2015	2020	2030	2035	2040	2050
PEF NEP	2.630	2.313	1.679	1.361	1.044	0.410
PEF WWB	2.630	2.484	2.193	2.047	1.901	1.610
GHG emission coefficient NEP	0.041	0.039	0.035	0.033	0.031	0.028
GHG emission coefficient WWB	0.041	0.049	0.064	0.071	0.079	0.094

Table 4

Combinations of retrofit measures for calculating payback times.

	Combinations					
	SH	DHW	ER	SH_DHW	SH_ER	SH_DHW_ER
Space heating (SH)	X			X	X	X
Domestic hot water system (DHW)		X		X		X
Envelope retrofit (ER)			X		X	X

NEP. The values for 2015 and 2050 are from [41], while the data in-between the years are linearly interpolated.

2.2.4.2. Economic aspects. Economic aspects are an important measure to assess the feasibility of different sustainable retrofit measures. Besides the annual operational costs for fuels, the costs for building transformations, including retrofit of the envelope and replacement of the building systems, are calculated. Costs for building envelope retrofit are based on the retrofitted element area, the required thickness of additional insulation combined with a cost factor given in [30]. The element area is calculated with the DM, whereas the insulation thickness of additional layers is extracted from the retrofit construction database. Costs for building systems are calculated based on the system peak power, which is an output from the DM, together with cost factor for variable and fixed costs separately [30].

As a result, the final payback time for different retrofit measures (shown in Table 4) are calculated.

The payback time is calculated by accounting the total investment costs and the annual savings in operational costs. Since future fuel prices are expected to change over time according to the SES 2050, the rise in fuel prices is also taken into account. The detailed calculation method is given in Appendix E.

3. Application on case studies

3.1. Case study description

Three different residential districts in Switzerland are taken as case studies: an urban and suburban district in the city of Zurich and a rural district in the village of Zerne, which is located in the mountainous region in Switzerland.

Fig. 5 shows the building configuration of the different case study districts. District 1 is an urban district, which consists of 227 multifamily buildings (MFB) in perimeter block development. The majority of the buildings are built before 1918. District 2 is a typical suburban district, mainly with detached buildings and a broad range of building ages. District 3 is located in a rural village and consists of detached, distributed, relative new or newly retrofitted buildings. District characteristics such as the total number of buildings, number of MFB and single family buildings (SFB), total floor area and yearly average outdoor temperature of 2015 are summarized in Table 5.

As a first step, the case study districts are simulated with the DM to generate demand profiles for the status quo (2015). To demonstrate the reliability of the approach a comparison between simulated and measured demand data for the rural case study is performed.

Further on, the RM is applied to all three case study districts to assess future energy performance potentials under the WWB and NEP scenarios of the SES 2050. In addition, several climate change scenarios are considered to demonstrate the climate impact specifically on the suburban district considering two different GHG concentration pathways.

3.2. DM results and validation

Hourly space heating and cooling, domestic hot water and electricity demand is simulated with the DM. Fig. 6 shows simulated hourly heating demand profiles in a day (24 h) for all buildings of the rural case study district. As it displays, variations in heating demand by time for each individual buildings are demonstrated. Occurrence of peak heating demand is different among the buildings due to the varied internal conditions during modelling. As a result, it avoids the effect of accumulation of simultaneous peaks for urban scale building simulation studies.

Since the use of the presented approach by policy and design decision makers depends strongly on the accuracy of the results, modelling results have been compared to available measured data from the rural case study. Measured data of the heat and electricity demand is available on building level, whereby the heat demand includes space heating as well as the DHW demand and is derived from annual fuel consumption data corrected by system efficiencies. For the considered buildings the heated floor area is reported by the house owner. These values sometimes deviate significantly from the building registry data, which are taken into account for the simulations. Due to this inconsistency some of the 115 buildings are excluded for the validation study, namely those where the floor area deviation lie above 100%. More information of the case study district including obtained measurements is given in [22].

Table 6 shows the measured and simulated district total heat demand of the remaining 78 buildings. Comparing the total heat demand of the complete district, a relative deviation of only –1.05% is obtained. Results show that the heating demand at district level can be predicted quite accurately.

Fig. 7 shows a comparison of the simulated and measured heat demand at individual building level, where a much higher deviation is obtained. This is not surprising since the heat demand significantly depends on a various number of factors, which are hard to predict on individual building level such as the exact user behaviour, the air leakage through the building envelope as well as the right construction details. In the simulation, older buildings tend to show too high heat demand while the heat demand of newer buildings is typically lower compared to measured data in most of the cases. This could be due to different factors, such as too low estimates for heat transfer coefficients of newer construc-

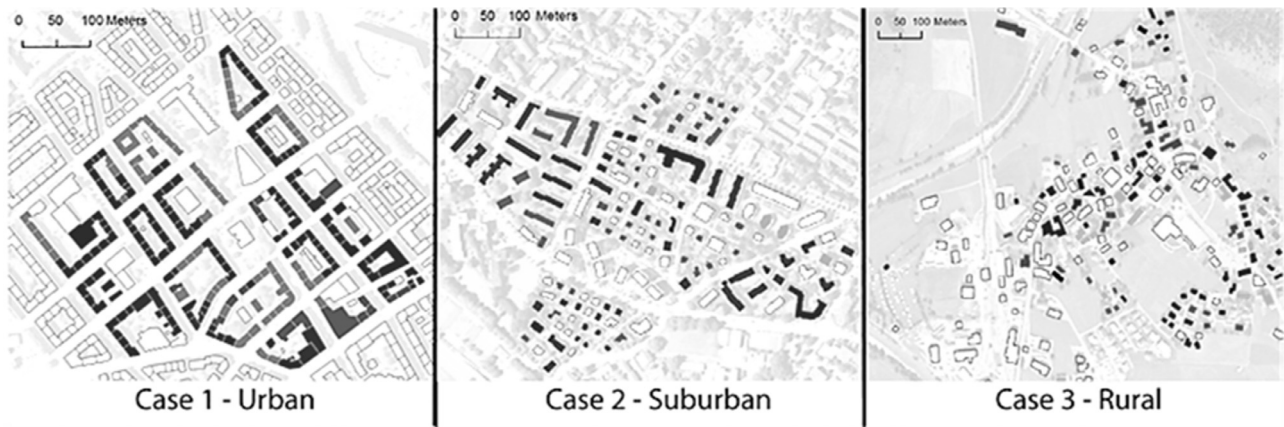


Fig. 5. Site overview of the case study districts.

Table 5

Case study district characteristics pertaining to number of buildings, MFB, SFB and avg. outside temperature.

Nr.	District name	# Buildings	# MFB	# SFB	Total floor area [m ²]	Average outdoor temperature [°C]
1	Urban	227	227	0	697,768	9.7
2	Suburban	100	78	22	246,076	9.7
3	Rural	114	91	23	86,638	7.5

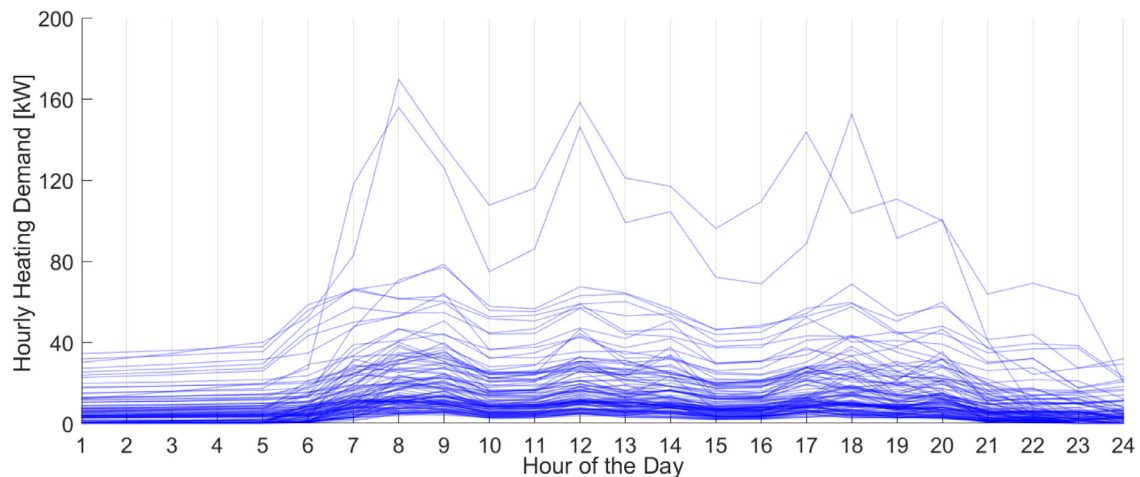


Fig. 6. Simulated hourly heating demand profiles in 24 h (01.01.2015) for the buildings in the rural case study.

Table 6

Comparison of simulated and measured total heating demand together with deviation in %.

	Measured	Simulated	Deviation [%]
Total heating demand [GWh/year]	3.366	3.331	−1.05

tion elements, too low infiltration rates while, different local climate conditions between the buildings, or most likely, windows of older buildings got replaced or are of a better type in reality than estimated in the simulation model, which is not reflected in the building database.

3.3. Retrofit of buildings

The two different transformation scenarios WWB and NEP, are applied to the three case study districts. The amount of retrofitted buildings as well as the impact of the different scenarios on the energy demand and investment costs are assessed in detail.

Table 7

Percentage of complete, partial and total retrofitted buildings until 2050 in each district.

	Partial retrofit [%]		Complete retrofit [%]		Total [%]	
	WWB	NEP	WWB	NEP	WWB	NEP
Urban	43.6	26	15.9	54.2	59.5	80.2
Suburban	27	32	17	41	44	73
Rural	22.8	31.6	5.3	18.4	28.1	50

The districts consist of buildings built within a wide range of construction year periods. Since retrofit rates are based on the construction year, districts with a bigger share of old buildings undergo higher transformation rates of the building envelopes. Furthermore, for older districts, the share of complete retrofits is usually higher than for newer ones. Table 7 shows the percentage of buildings in each district that got an envelope retrofit for both scenarios separated by complete and partial retrofit by 2050. In the urban case, a relative old district, 80% of all the buildings will be retrofitted until 2050 (NEP). In contrast, only about 50% of the

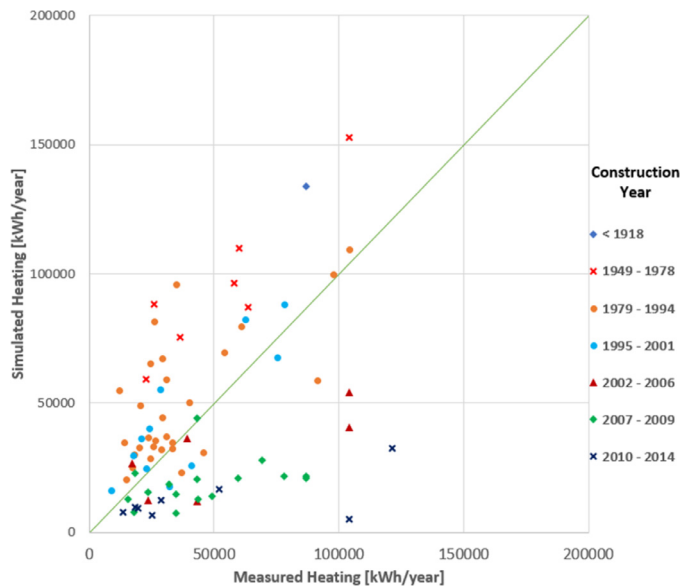


Fig. 7. Comparison of simulated and measured heating demand at building level.

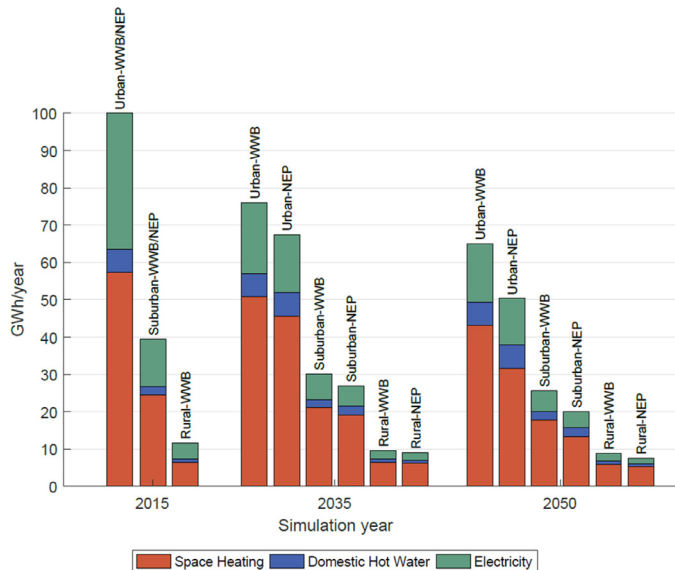


Fig. 8. District total energy demand and its transformation until 2050 for the different districts and transformation scenarios.

buildings in the rural case with lots of new buildings are retrofitted by 2050 (NEP).

3.3.1. Reduction in demand

Fig. 8 shows the reduction of the total energy demand of the districts separated by the heating demand for space heating, DHW and the electricity demand for appliances and lighting for the current (2015) and two future time steps (2035 and 2050) for both scenarios (WWB and NEP).

The applied retrofit of the building envelope has a significant impact on the total heating demand for space heating. The reduction in electricity demand is based on the projected gain in efficiency of lighting and electrical appliances. The DHW demand is assumed to be constant in future, due to the assumption that the amount of required litres per person will not change in the future.

To further examine the changes in space heating demand: it shows high reduction in heating demand of up to 45% in the NEP scenario by 2050 for urban and suburban district with older

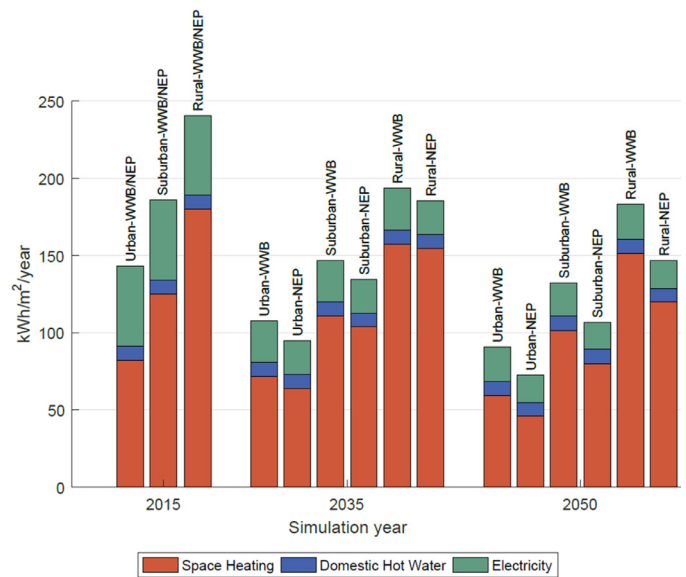


Fig. 9. District average floor area specific energy demand and its transformation until 2050 for buildings built before 1918.

Table 8

Non-renewable primary energy consumption and GHG emissions and its transformation until 2050.

	Total PEN [TJ-eq/year]			Change [%]	
	2015	2050 WWB	2050 NEP	WWB	NEP
Urban	685.3	278.7	94.8	−59.3	−86.2
Suburban	262.8	105.8	31.5	−59.7	−88
Rural	97.2	29.2	6.8	−70	−93
	Total GHG [kt CO ₂ -eq/year]			Change [%]	
	2015	2050 WWB	2050 NEP	WWB	NEP
Urban	27.2	16.8	6	−38.2	−77.9
Suburban	11.1	6.4	2	−42.3	−82
Rural	2.5	1.7	0.4	−32	−84

buildings. This is consistent with the high percentage of retrofitted buildings in those districts. In the rural district, the heating demand is only reduced by 20% in the NEP scenario due to high amount of relatively new or already retrofitted buildings.

Fig. 9 shows the development of specific energy demand per average floor area for buildings built before 1918. Space heating demand reduction is higher for the urban district (consisting of more attached buildings) than the suburban district (consisting of more detached buildings). Moreover, specific heating demand in the rural case is relatively high, mainly due to the cold climate in the mountainous region.

3.3.2. System transformations

To examine the changes in system transformation, Fig. 10 shows for all districts, systems that are installed today (2015) and different transformations in the future. In the urban and suburban districts, oil and gas systems are predominant currently, while in the rural district a high share of oil and electric heating systems is found. By applying system development according to SES 2050, it completely transforms the current pattern and replaces oil, coal and electricity systems with more sustainable solutions such as heat pumps and solar or biogas based systems. The system transformation has a significant impact on the reduction in primary energy consumptions and GHG emissions for all districts.

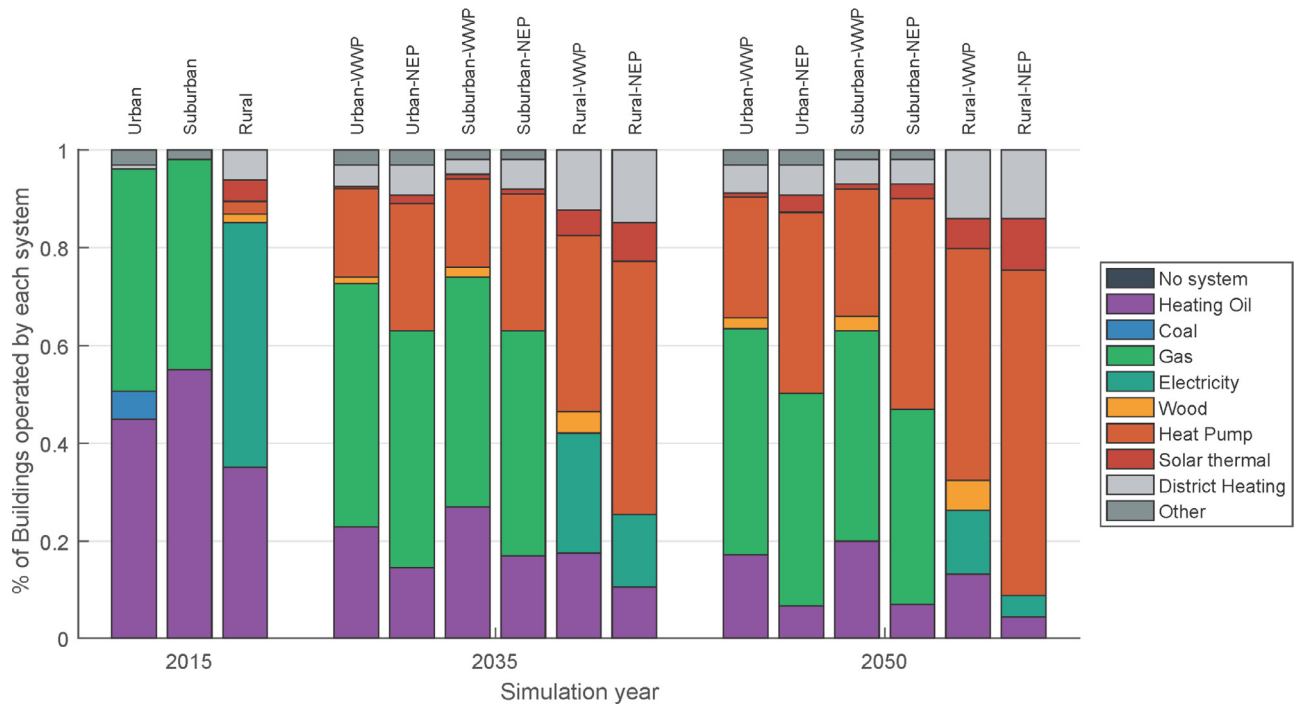


Fig. 10. Heating system shares and transformations until 2050 for the three districts and the different transformation scenarios.

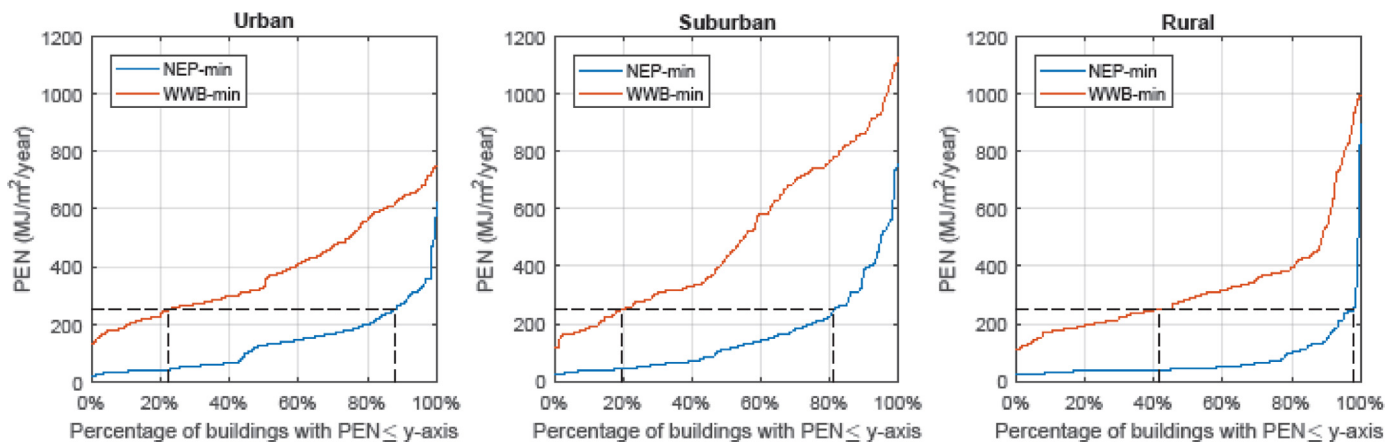


Fig. 11. Percentage of buildings reaching the primary energy consumption target of the 2000-Watt Society for the WWB and NEP scenarios in 2050.

3.3.3. Primary energy and GHG emissions

Table 8 shows the district total primary energy consumption and GHG emissions for operation in 2015 and 2050 as well as their relative change. In the WWB scenario, in all the districts a reduction of non-renewable primary energy consumption (PEN) of about 60% can be achieved by 2050, while a reduction of almost 90% is obtained in the NEP scenario. Following the path of the NEP scenario, GHG emissions can be reduced by up to 80% until 2050 compared to today's emissions.

Fig. 11 shows a normalized histogram for each district with accumulated percentages of buildings in a certain range of PEN consumption for operation in 2050. In the NEP scenario, more than 80% of the buildings in the urban and suburban district reach the PEN target of 250 MJ-eq/(m²*year) by 2050 as outlined in Table 1. In the rural district about 98% of all the buildings reach this target. The percentage of buildings reaching the PEN target is significantly lower in the WWB scenario with only about 20% for the urban and suburban district and 40% of the rural case study. As for the GHG

emissions, a similar distribution can be obtained, but fewer buildings reach the target of 5 kg CO₂-eq/(m²*year). Only 40% of buildings in the urban and suburban and 76% of buildings in the rural case study reach the target in the NEP scenario, while no building reaches the target in the business as usual WWB scenario.

Fig. 12 shows a normalized histogram of embodied primary energy included in the retrofit measures of the buildings until 2050. Results show that for both scenarios the 2000 Watt Society target of 60 MJ-ew/(m²*year) can be reached for all buildings in the urban case and for around 90–95% for the suburban and rural cases. A similar distribution and target achievement is obtained for embodied GHG emissions.

3.3.4. Economic aspects

Economic aspects, such as total investment costs and payback times, are an important indicator in comparing the environmental and economic benefits of different transformation scenarios. Fig. 13 shows the total investment costs for the different retrofit

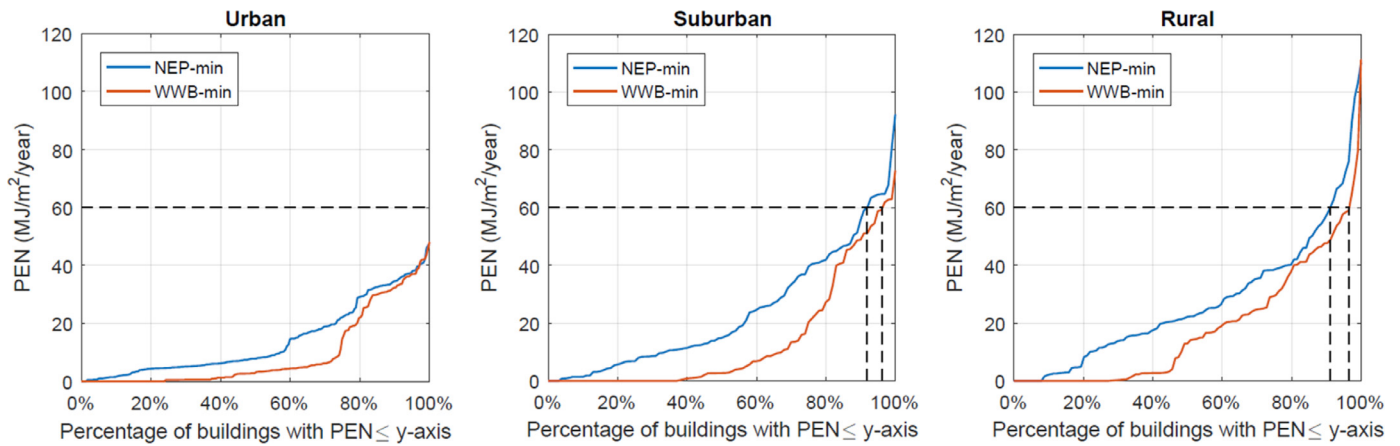


Fig. 12. Percentage of buildings reaching the embodied PEN target of the 2000-Watt Society by 2050 for retrofit measures of buildings (target indicated in red).

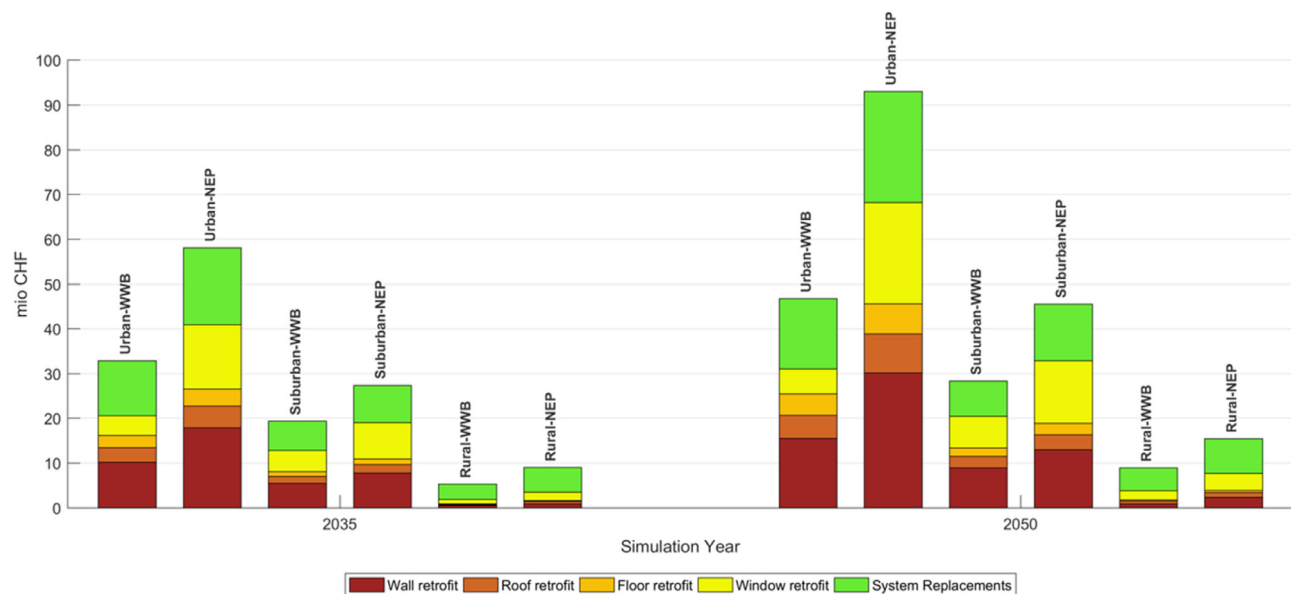


Fig. 13. District total retrofit investment costs for the different transformation scenarios.

Table 9

District total reduction in annual primary energy consumption by 2050 for a certain investment.

	Reduction in annual PEN consumption per CHF [$\frac{MJ}{CHF}$]	
	WWB	NEP
Urban	−3.33	−2.86
Suburban	−2.44	−2.63
Rural	−4.37	−3.23

measures and system replacements in the case study districts for the WWB and NEP scenario. The transformation measures in the NEP scenario implemented until 2050 are almost twice as expensive as in the WWB scenario. In older districts (urban, suburban), system replacement costs account for about 1/4 of the total investment costs, while in newer districts (rural) costs for new systems account for about half of the total investment costs since fewer buildings require a retrofit of the envelope.

Table 9 shows the average reduction in annual primary energy consumption that is met by 2050 on investing one Swiss Franc (CHF). For the urban and rural scenario, the WWB scenario shows higher reduction in PEN per invested money. In the suburban case,

Table 10

District average payback times for different retrofit combinations in [years].

	SH WWB	DHW	ER	SH_DHW	SH_ER	SH_DHW_ER
Urban	20.5	8.8	10.7	17.0	–	9.0
Suburban	15.5	–	16.9	13.8	–	16.0
Rural	7.8	15.0	20.9	14.5	–	13.7
NEP						
Urban	18.4	5.9	12.7	12.2	9.0	14.5
Suburban	17.0	11.1	16.0	13.0	10.0	18.0
Rural	25.3	13.7	20.3	10.8	–	16.0

the NEP scenario is more beneficial since a higher reduction in primary energy consumption is obtained for a certain investment. Overall, the most beneficial case according to primary energy reduction for a certain investment shows the rural district in the WWB scenario with $-4.37 \frac{MJ}{CHF}$.

Table 10 shows the average payback time of the six different retrofit combinations (see Table 4), excluding negative payback time that can occur in case of a system change to a more expensive

Table 11
Average monthly outside dry bulb temperatures [°C] for different climate change scenarios.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Avg
Standard	0	1	4	7	11	14	17	16	14	9	4	1	8.17
Rcp 4.5	1	4	7	9	12	14	18	17	14	10	3	1	9.17
Rcp 8.5	2	5	2	9	10	17	19	20	16	9	7	−2	9.5

sive fuel (e.g. oil to gas). Results show that a replacement of both systems for space heating and DHW (SH_DHW) at the same time step is usually more beneficial than just replacing the space heating system (SH). Furthermore, a retrofit of the envelope (ER) also shows quite a short payback time, which is mostly lower if combined with a system replacement (SH_DHW_ER) at the same time step.

The payback time of retrofit measures at the envelope (ER) are correlating with building age. In the older districts (Urban and Suburban) a shorter payback time is obtained while in the newer district (Rural) the payback time is significantly longer. Therefore, the relative retrofit costs compared to its reduction in demand are higher for newer buildings with an already well insulated envelope. Combining retrofit of the envelope with system replacements, payback times are dependent on the building age as well as on the systems. Overall, the payback time for system replacements is highly dependent on the previous and new system and its efficiency and fuel costs. The gathered data allows for a detailed analysis of the most sustainable and financially beneficial retrofit measures on building level by comparing different combinations of system change and envelope retrofit.

3.4. Effects of climate change

The suburban district in Zurich is considered for the assessment of the climate change impact on energy demand and emissions of a district. For the analysis, future climate scenarios from the HIRHAM climate change model for the GHG concentration pathways rcp 4.5 and rcp 8.5 are compared to the scenario without any climate change.

Table 11 shows the average monthly outdoor dry bulb temperature of the standard climate scenario without climate change and the temperature data from the HIRHAM rcp 4.5 and rcp 8.5 scenario in 2050. The annual average temperature is rising from 8.17°C in the standard scenario to 9.5°C in the HIRHAM rcp 8.5 scenario. While in the rcp 4.5 scenario in almost every month the average temperature is higher than in the standard scenario, the rcp 8.5 scenario shows higher fluctuations in temperatures with significantly warmer summer months but also some colder winter months.

Fig. 14 shows the annual average number of hours where cooling is required in a residential building to prevent overheating. In the Standard climate scenario, in only about 200 h (~8 days) throughout a complete year, space cooling is necessary to keep the indoor temperature below the cooling set point, which is defined as 26°C. This relatively small number is the reason why there is typically no cooling system installed in residential buildings today. However, results show that overheating hours will change considerably in future.

Without any climate change, the amount of hours when cooling is required is doubled in the WWB scenario and tripled in the NEP scenario until 2050. This could be due to better insulated buildings and tighter envelopes, which on the one hand reduce the heating demand in winter due to less heat loss through the façade but also keeps internal heat gains enclosed in the building during summer time. This effect could be reduced by increasing ventilation rates,

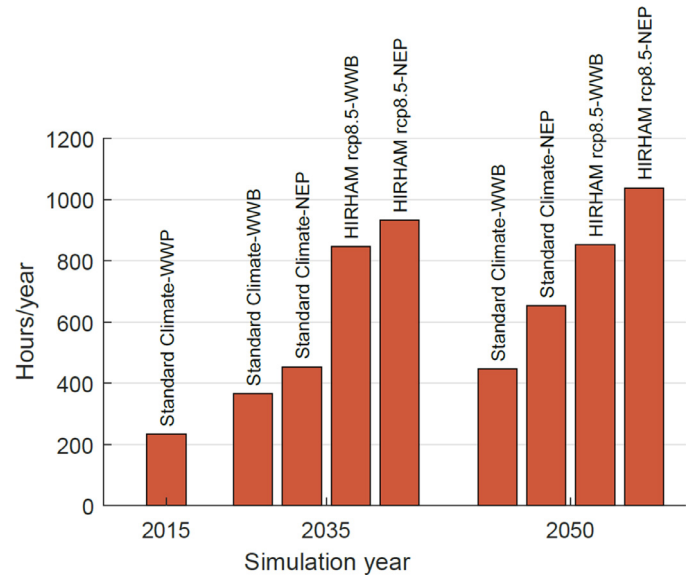


Fig. 14. District average annual cooling load hours.

which is presently not taken into account in the model, but could be incorporated.

Due to climate change and higher annual temperatures in average, the number of hours when cooling is required is increased to more than 1000 h in the HIRHAM rcp 8.5 scenario (about 41 days per year). Therefore, it is likely that in future, depending on the actual climate change, cooling of residential buildings will be crucial to maintain a comfortable indoor climate.

According to the total heating demand for space heating in 2050, the climate change scenarios shows lower demand of about −11% (rcp 4.5), respectively, −4% (rcp 8.5) compared to the scenario without climate change due to higher outdoor temperature in winter.

4. Conclusion

The presented CESAR modelling tool offers an easy but comprehensive approach to model the present and future energy performance of buildings in districts or even complete cities and communities in an automated way. Fast access to simulated hourly resolved energy consumption data, primary energy and GHG emissions as well as embodied energy and costs due to future transformations of districts is provided. The resulting data allows to further assess the development of distributed energy systems by offering detailed current and future demand profiles for energy hub models.

Furthermore, different future transformation scenarios and their impact on real districts and building configurations can be compared to each other. This is crucial for the evaluation of sustainable retrofit measures and the assessment of saving potentials in energy demand, primary energy consumption and GHG emissions. The detailed and complete set of results, including energy demand,

systems, embodied energy, costs for retrofit and amortization times allows to detect the most viable transformation measures according to environmental and economic aspects. The flexibility of the method further allows to model political strategies and their effect on the energy demand of the building stock. Besides that, the model offers the possibility to assess the performance of buildings and their energy demand under different climate change scenarios.

Comparing the three different case studies in Switzerland and their future transformation under the *WWB* and *NEP* scenario reveals a high difference according to future energy consumption and emissions. The impact of the different scenarios is highly dependent on the existing district configuration (building types, building age, location, construction and neighbourhood) as well as on the existing system types. According to the 2000-Watt Society targets for 2050, only under the *NEP* scenario a reasonable amount of buildings is reaching the target for PEN and GHG emissions until 2050, neglecting the impact of climate change, which causes a significant increase in cooling demand. To cope with newly evolving energy demands for cooling of residential buildings, sustainable and energy-efficient solutions are required to reach the targets of the 2000-Watt Society.

Economically, in most of the cases, the retrofit measures are financially beneficial and the invested money is paid back by savings in operational costs already after a few years.

5. Outlook

There are numerous of possibilities to further improve and extend the model. A big step, which is planned, is to add other building types, such as office or administrative buildings to the model. This requires additional input parameters describing constructions,

internal gains and retrofit transformations for those building types. Additional improvements pertain to the reduction of active cooling loads through integrating night ventilation schemes and the adoption of blinds and their associated deployment schedules.

The selection of buildings that are retrofitted and get a new heating system could be modified to follow a “worst-buildings-first” approach instead of a random selection. In such a scenario, the buildings with the highest floor area specific energy demand for space heating would be retrofitted first. A further avenue, which will be explored in the future, is to link the *CESAR* model with an energy hub optimization model [42,43], which allows to select next to the optimal envelope retrofitting scenario also the optimal system selection for each individual building.

Acknowledgements

This research has been financially supported by *CTI* within the *SCCER FEE&D* ([CTI.1155000149](#)) and by *SNF* within the *NFP 70* program “Energiewende” project *IMES-BP* ([407040_153890](#)).

Appendix A. Construction information

Construction information for wall, roof and basement until 1994 are based on [44], and from 1994 until 2007 are based on *Bauteilkatalog* [45], which are combined with typical insulation thickness values extracted from [46].

For newer constructions, standard configurations from the *Bauteilkatalog* are combined with a certain insulation thickness to reach Swiss standards for new built buildings based on the norm *SIA 380* [47]. This norm provides minimal and target requirements, where the minimal requirements have to be met according

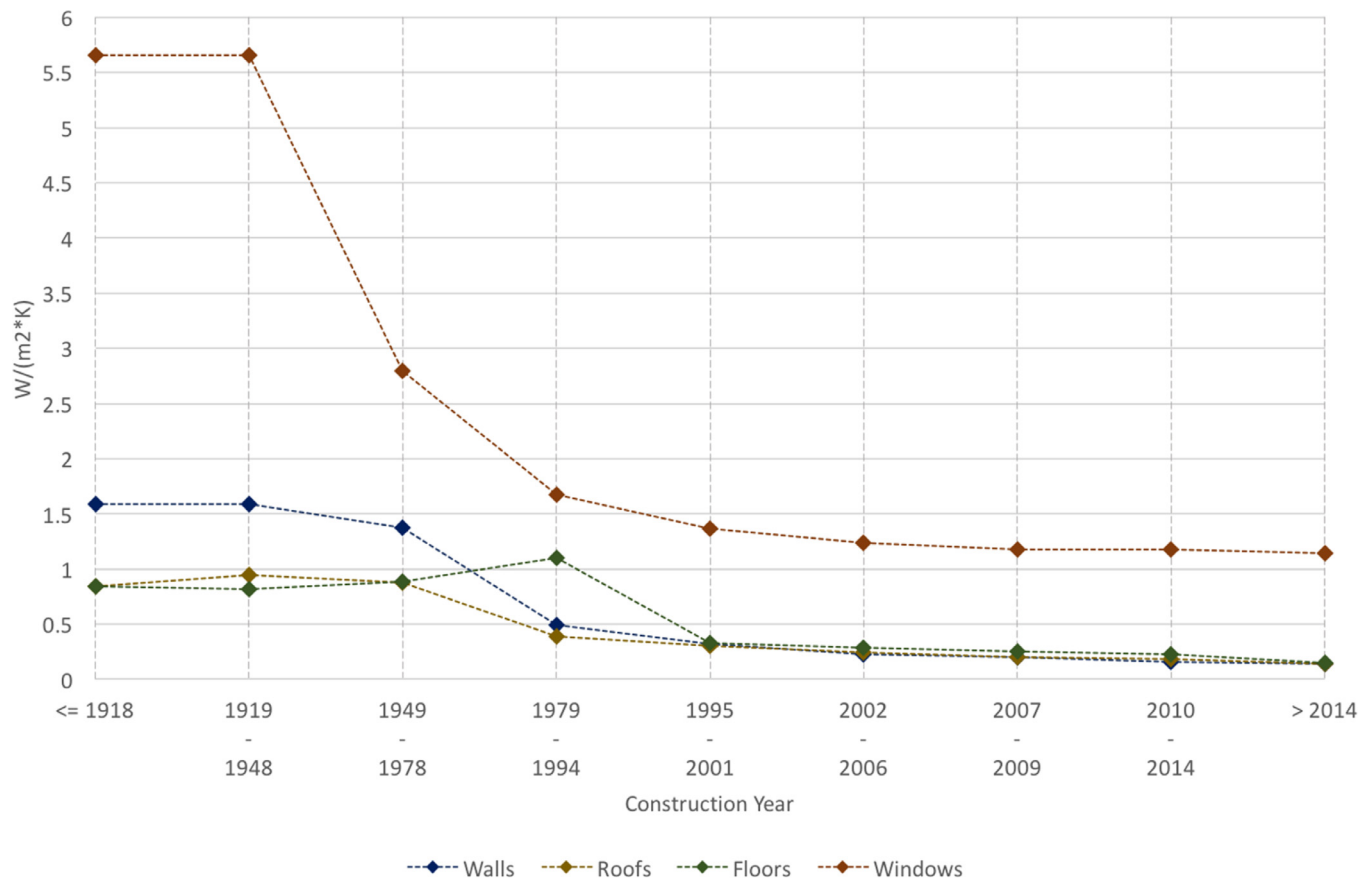


Fig. A. 1. Nominal *U*-values of construction elements for the 9 available construction year periods.

to Swiss building regulations, while the target values define the goal according to insulation properties of construction elements. The insulation properties of the newest constructions are based on the minimal normative requirements (buildings built between 2010 and 2014) until the target normative requirements (buildings built later than 2014). The obtained U -values of the construction setup for buildings built after 2010 are in accordance with measurements performed in Zurich [48]. Typical material values for wall, roof and basement constructions are based on an online database [49].

U -Values of windows are based on [50] and again verified by measured values from [48]. The layers of windows, including the material specifications, are computed with the Berkeley Lab Window 7.4 software [51].

Buildings and constructions are categorized into nine construction year periods. To represent the variation of constructions within the same age class according to materials and insulation properties, multiple, slightly varying construction setups for walls, windows, roofs and basements are available for each construction year period. Upon user preference, a construction element within one age class is either randomly assigned to a building, or an element with a nominal insulation value for each age class can be selected which ensures comparability between different simulation runs. Fig. A.1 shows the nominal heat transfer coefficients (U -values) of the different elements for the implemented construction year periods. Available materials and constructions are structured into a database, which is linked to the DM and used to assign constructions to the individual IDF files.

Appendix B. Infiltration rates

Fig. B.1 shows infiltration rates together with window to wall ratios (WWR) for all building age categories. Infiltration rates for buildings built until the year 1994 are based on [52] and complemented until 2014 based on an interpolation between the last value from [52] and the Minergie minimal requirement of 0.05 ACH [53]. This approach is based on the assumption, that newer buildings (>1978) generally have a tighter building envelope.

Appendix C. Internal conditions

The set of scalar parameters required by the DM to represent the internal conditions of the building includes: (i) the nominal floor area per person (m^2/P), (ii) the installed lighting capacity (W/m^2), (iii) installed appliances capacity (W/m^2), (iv) hot water demands (W/m^2), (v) thermostat settings ($^\circ\text{C}$), and (vi) required ventilation rates ($\text{m}^3/\text{m}^2/\text{h}$). Additionally, information about the temporal variation of all of these aspects is required in the form of hourly schedules for a full year.

As was discussed in Section 2.1.3, in order to represent building diversity, probability distributions are assigned to each of the aforementioned scalar parameters. For the first four scalar parameters mentioned above, the norm SIA 2024 [27] provides nominal values as well as a range in which they are expected to fall. Using this information, a triangular distribution is assigned following the approach in [54] with the nominal value being the distribution's mode and the range used for the minimum and the maximum values of the distribution. For the last two parameters, namely the thermostat and the ventilation settings, normal distributions are assigned similarly to [55,56]. The nominal value for SIA 2024 is used as the mean, while the standard deviations are taken as 1°C for the thermostats and 10% of the mean value for the ventilation settings.

Regarding the second type of input, namely the occupancy and activity schedules, SIA 2024 provides typical daily schedules for occupancy and appliance usage, assumed to be repeated for each day of the year (with the exception of weekends for some building types). The schedules for lighting, hot water, thermostat and ventilation settings are assumed to be the same as the occupancy schedule (with the exception of night hours when lighting and hot water is not used). Starting from this 'nominal' yearly schedule, we introduce the desired variability in two steps: the first is labelled as *vertical variability* and it consists of randomly perturbing each hourly value around its nominal value (e.g. by $\pm 15\%$). This, for instance, leads to a differentiation of the number of people present at 3 p.m. in an apartment from day to day. The second step is labelled as *horizontal variability*. The approach consists of the creation of blocks of hourly periods for the 24 h of each day (e.g. [00:00–06:00], [07:00–09:00], etc.) and within these blocks

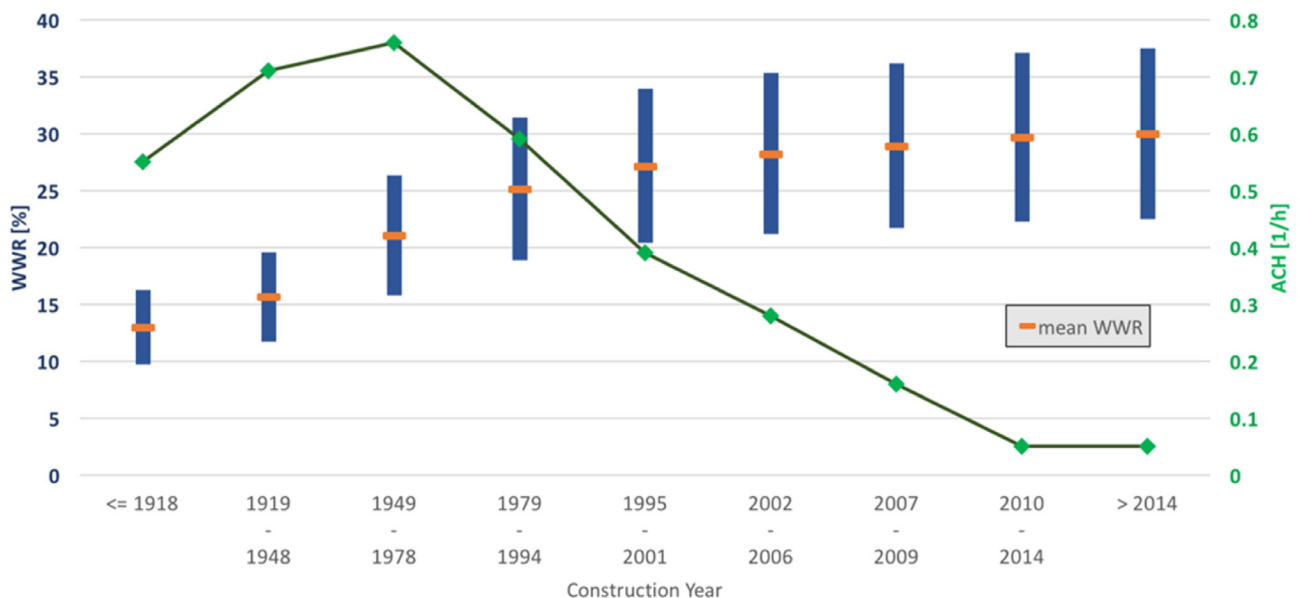


Fig. B. 1. Archetypical WWR range in blue with the mean WWR in orange and the infiltration rate in air change rate per hour (ACH) in green for the 9 construction year periods.

shuffling the nominal schedules values with each other. This approach allows us to maintain the order of actions causing specific energy patterns (e.g. processes happening in the morning versus processes happening at noon) while introducing some randomness within the blocks (e.g. the lights for a room could be turned on at 7 a.m. on one day and at 8 a.m. on another). Overall, thus, taking the usage of appliances as an example, from one day to the other, the number of appliances being turned on will differ in terms of time, but also in terms of power required. By repeating this process for each building type, we create a bank of all the schedules required, from which we can sample a different schedule for each building, hence, creating a variation among buildings in the temporal dimension as well.

Appendix D. Retrofitting assumptions

Element specific retrofit rates are given in [35] for flat roofs, pitched roofs, walls, windows and ground floors as annual rates for different retrofit periods separated by the construction year. The annual retrofit rates for flat roofs and pitched roofs are averaged, since the exact roof type is not known in the model. Table D.1 shows aggregated retrofit rates for buildings built between 1975 and 1985 for the retrofit periods, which are available in the RM. For this example: between 2015 and 2020, 12% of the buildings get a retrofit of their windows, 4% get a retrofit of their walls, 5% get a retrofit of their roof and 2.5% get a retrofit of their ground floors. But these rates do not state, how many buildings get a retrofit combination of multiple elements.

To extract retrofit rates for element combinations, it is assumed, that as many elements as possible are retrofitted at the same building in the same period by maintaining the shares indicated in Fig. D.1. Element specific retrofit rates from [35] are given only for four different construction year periods, namely <1947, 1947–1975, 1975–1985, 1985–2000, while the SES 2050 [3] provides such overall retrofit rates for much more construction year periods. Therefore, the rates for element retrofit combinations are transformed by using Eq. (D.1) to the shares for the different combinations. Eq. (D.1) gives an example for the share of complete retrofitted buildings in the retrofit period 2015–2020 and built between 1975 and 1985.

$$\text{Complete Retrofit Share} = \frac{\text{Complete Retrofit Rate}_{\text{Swiss Building Stock}}}{\text{Overall Retrofit Rate}_{\text{Swiss Building Stock}}} \times 100 = \frac{2.5\%}{12\%} \times 100 = 20.8\% \quad (\text{D.1})$$

As an example, Fig. D.1 shows all these partial retrofit shares of the possible combinations of envelope elements for single family buildings (SFB) built between 1975 and 1985 for the 5 retrofit periods in the WWB scenario.

Finally, assumptions on partly retrofit rates together with the overall retrofit rates from the SES 2050 are provided to the RM, where the actual rate for buildings that get a complete retrofit is derived by Eq. (D.2)

$$\text{Complete Retrofit Rate} = \frac{\text{Complete Retrofit Share}}{100} \times \text{Overall Retrofit Rate}_{\text{EnergyStrategy}} \quad (\text{D.2})$$

Table D

Aggregated retrofit rates in [%] for different construction elements and retrofit periods for buildings built before between 1975 and 1985.

	2015–2020	2020–2030	2030–2035	2035–2040	2040–2050
Window	12.0	20.0	6.5	6.5	5.0
Wall	4.0	8.0	3.0	3.0	3.0
Roof	5.0	9.0	3.2	4.0	6.5
Floor	2.5	5.0	2.5	2.5	5.0

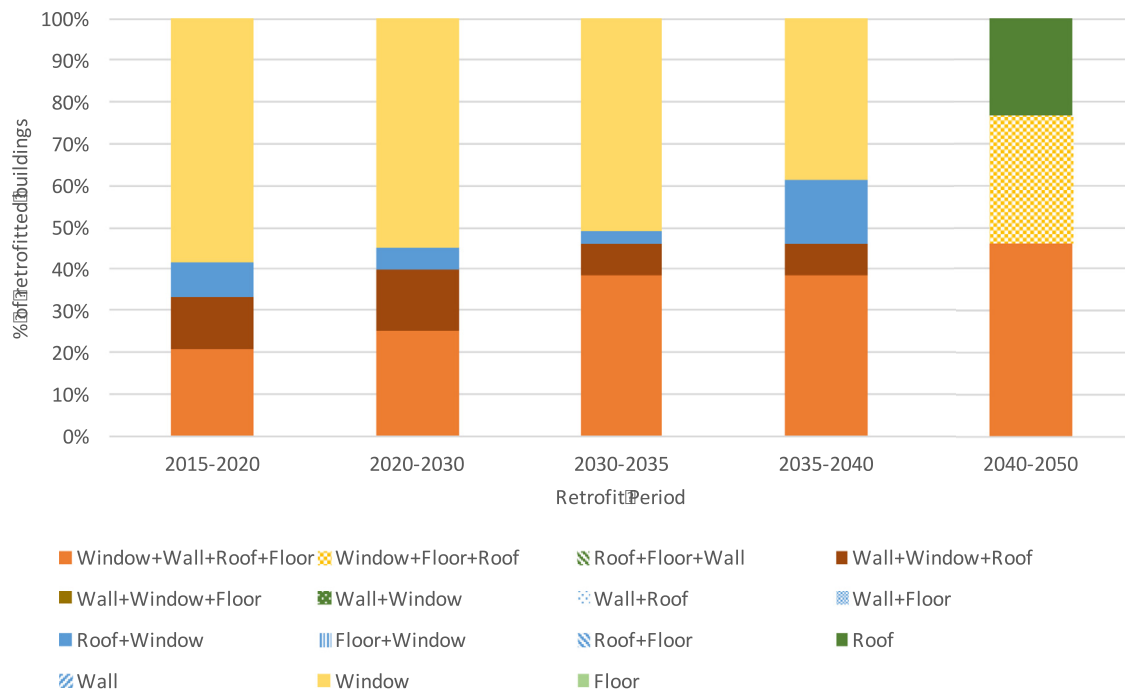


Fig. D. 1. Partial retrofit shares in the WWB scenario for the 15 envelope element combinations for SFB's built between 1975 and 1985.

In case of a retrofit of the building envelope, additional insulation is added to the original constructions until required U -values for retrofitted constructions according to SIA 380 are met. The resulting retrofit constructions are structured in a database similar to the non-retrofitted constructions and linked with the RM.

Appendix E. Economic analysis for payback time calculation

The detailed calculation methodology is described for the Case SH_ERas an example, where the envelope is retrofitted and in the same retrofit period the space heating system is replaced. As investment costs C_{Invest} , the total costs for the retrofit of the envelope and the replacement of the heating system are considered. The annual operating respectively fuel costs before retrofit $C_{op, BeforeRet}$, with respect to the rise in price, can be calculated by Eq. (E.1) for any future year t . Since retrofit measures at the envelope only have an impact on the heat demand, the heat demand before retrofit $Q_{h, BeforeRet}$ [$\frac{kWh}{Year}$] is used together with the cost factor of the heating fuel $C_{hFuel, BeforeRet}$ [$\frac{Rp}{kWh}$], the annual rise in price factor $r_{PhFuel, BeforeRet}$ [%] and the efficiency $\eta_{hSys, BeforeRet}$ [%] of the previous heating system.

$$C_{op, BeforeRet}(t) = \frac{Q_{h, BeforeRet}}{\eta_{hSys, BeforeRet}} * \frac{C_{hFuel, BeforeRet}}{100} * (r_{PhFuel, BeforeRet})^t \left[\frac{CHF}{Year} \right] \quad (E.1)$$

Eq. (E.2) is used to derive the operating costs after retrofit $C_{op, AfterRet}$, which is based on the heat demand after retrofit of the envelope and the efficiency, fuel cost factor and the rise in prices factor of the new heating system.

$$C_{op, AfterRet}(t) = \frac{Q_{h, AfterRet}}{\eta_{hSys, AfterRet}} * \frac{C_{hFuel, AfterRet}}{100} * (r_{PhFuel, AfterRet})^t \left[\frac{CHF}{Year} \right] \quad (E.2)$$

The payback time (PT) is calculated by Eq. (E.3) which is basically the division of the invested costs by the accumulated savings in operational costs from before to after retrofit of the envelope and replacement of the heating system.

$$PT = \frac{C_{Invest}}{\sum_{t=1:PT} (C_{op, BeforeRet}(t) - C_{op, AfterRet}(t))} [Years] \quad (E.3)$$

Since Eq. (E.3) cannot be explicitly solved, an iterative approach is applied. A similar calculation methodology is implemented for the other five measures.

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